Arctic Ozone Depletion Observed by UARS MLS during the 1994-95 Winter

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Introduction

The northern hemisphere (N II) lower stratosphere was unusually cold in 1)ec 1994 and Jan 1 995 and temperatures low enough for polar stratospheric ('1011(1 (PSC) formation persisted until mid-March 1 995; the polar vortex was exceptionally strong throughout the winter [*Zurek et a l.,* submitted to *Geophys. Res. Lett.*]. Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) measurements during the previous 3 NH winters showed enhanced chlorine monoxide (ClO) in the N}-] vortex comparable to the southern hemisphere (S}1) [*Waters et al.,* 1 995], and evidence for ozone (O_3) depletion in the NH lower stratosphere [*Manney et al.,* 1994; 1995a, b]. N]] 03 loss varies markedly due to interannual variability in the duration, location and extent of temperatures low enough to form PSCs, and in 03 transport [e. g., *Manney et al.,* 1995b]. We present observations from h'11, S in late Dec 1994 and Feb and early Mar 1995 that indicate significant O_3 depiction, and compare these with observations during other N]] winters observed by MLS.

Data and Analysis

The MLS data and validation are described by *Froidevaux et al.* [199(L] for O_3, and by *Waters et al.* [1995] for ClO. Precisions (rms) of individual O_3 (ClO) measurements are ~0.2 ppmv (~0. 5 ppbv), with absolute accuracies of 15-20% in the lower stratosp here. The M LS scan mechanism developed problems in late 1994, and was used sparingly thereafter to conserve instrument life. M LS obtained full vertically scanned data on 21 I)(T 1994, 1, 3, 8, 14, 21, '2s Feb, and 6, 8 and 10 Ma]' 1995. MLS tracked the atmospheric limb at 18±2.5 km without vertical scanning from 22-30 Dec 19!)4 and from 2 Feb-9 Mar 1995, excluding the scanning days; this allowed limited daily atmospheric monitoring. O_3 and ClO at 46 hPa are retrieved from these "non-scanning" measurements, but with poorer vertical resolution than the scanning measurements.

Because enhanced ClO is highly localized both horizontally and vertically, with its maximum near 46 hPa, a reasonable estimate of vortex-averaged ClO on the 465 K isentropic surface (near ~50 hPa inside the vortex) can be made from non-scanning data. An empirically-derived overall offset of ~0.3 ppbv in ClO between non-scanning and scanning data, attributed to the differing vertical resolutions, is added to the non-scanning vortex averages.

MLS data are gridded by binning and interpolating 24 h segments of data. Scanning data are interpolated to isentropic surfaces using United Kingdom Meteorological Office (UKMO) [*Swinbank and O'Neill,* 1994] temperatures. Potential vorticity (PV) is calculated from UKMO analyses. Three-dimensional (3D, including diabatic effects) O_3 transport calculations are done using UKMO horizontal winds, computed diabatic descent rates, and a reverse trajectory procedure [*Manney et al.,* 1995a, b].

Lower Stratospheric Ozone and" C1O

Fig. 1 shows 465 K UKMO mini mum temperature, and vortex-averaged ClO and O_3 in the *N]]* during 1994-95, compared with the previous 3 winters. Temperatures fell below the type I PSC formation threshold (~195 K) in early Dec 1994 (Fig. 1a) and were near the type II PSC formation threshold (~188 K) from ~15 Dec 1994 through ~15 Jan 1995. Although UKMO temperatures are only below the type II threshold on a few days, comparisons with US National Meteorological Center (NMC) and radiosonde temperatures indicate that UKMO values are ~1-4 K higher than the best estimate of minimum temperature throughout this period [*Manney et al.,* submitted to *J. Geophys. Res.*]. The NMC data show late Dec 1994 temperatures that were lower than those in any of the previous 16 NH early winters, early Jan 1995 temperatures that were more continuously low, and temperatures below the type II PSC threshold for ~20 days during the winter (as many or more days than in any of the previous 16 years) [*Zurek et al.,* submitted to *Geophys. Res. Lett.*]. Strong warmings in late Jan

1995 raised temperatures to near type I PSC threshold values.

Vortex-aver:Lg(:cl Ml,S ClO is shown in Fig. 1b. In late Dec 1994, ClO was observed to be considerably higher than during any of the previous 3 years. When MLS looked south during Jan, the vortex remained shifted off the pole and the unusually large cold region was mainly in sunlight, providing conditions favorable to continual production of ClO. As expected, ClO was enhanced throughout the vortex when MLS resumed NH measurements on 1 Feb 1995. Minimum temperatures rose above the PSC threshold on ~8 Feb 1995 (Fig. 1a) and ClO decreased rapidly (Fig. 1b); on 14 Feb only small regions of ClO > 1 ppbv were observed. ClO decreased further after 14 Feb (part of this decrease may be due to MLS observing high latitudes mainly in darkness at this time), but then increased again as minimum temperatures fell in late Feb and early Mar. By 8 Mar, vortex ClO values were enhanced to the level observed on 14 Feb (and also near values observed a year earlier during a late cold spell in early Mar 1994).

Fig. 2 shows 465 K O_3 maps during the 1994-95 winter on several days with scanning measurements. Vortex O_3 on 21 Dec 1994 was slightly lower than that in the previous 3 years. 465 K vortex O_3 decreased substantially between late Dec 1994 and early Feb 1995, and early Feb O_3 (Fig. 1c) was lower than in any of the previous 3 NH winters. Comparison of Figs. 2a and 2b reveals a significant reduction in O_3 throughout the vortex. The rate of O_3 decrease between late Dec and early Feb was similar to that in Feb and Mar 1993, with a net decrease in vortex-averaged O_3 of ~15%. The 1994-95 decrease is consistent with that inferred from lidar observations for the same period at Eureka (80°N, 86°W) [*Donovan, et al.,* submitted to *Geophys. Res. Lett.*].

The expected O_3 distribution due solely to 3D transport (open symbols in Fig. 1c) is calculated [*Manney et al.,* 1995a, b] to estimate how much O_3 depletion was masked by resupply via diabatic descent, and to explore the possibility that O_3 may have decreased because lower O_3 air was drawn into the vortex. These calculations show no evidence for intrusion of low latitude air before late Jan. As expected, 3D transport tends to increase

O_3 slightly during late Dec (Fig. 1c, open triangles), with more rapid increases in late Jan and early Feb. Vortex-averaged O_3 in early Feb 1995 would have been ~3.1 ppmv if only transport were important, as opposed to the ~2.6 ppmv observed. This implies that the observed decrease was due mainly to chemistry, and indicates that ~1/4 of the chemical destruction was masked by transport. Both the O_3 decrease between late Dec and early Feb, and the resupply of higher O_3 by transport, were similar in magnitude to those in Feb/ Mar 1993 [*Manney et al.,* 1995a]. However, in contrast to 1992-93, most of the O_3 destruction near 465 K in 1994-95 took place earlier in the winter when 1) less of the high latitudes were exposed to sunlight (so chemical processing was possible in a smaller area), and 2) less ozone had previously been transported to the lower stratospheric vortex by diabatic descent (so lower minimum values of 465 K O_3 were observed during the 1994-95 winter).

Intrusions of low O_3 air into the vortex in early Feb decrease computed vortex-averaged O_3 by no more than ~0.15 ppmv (Fig. 1c, open diamonds). The observed O_3 decrease between 1 and 8 Feb may have been partly caused by such an intrusion]. Observed vortex-averaged lower stratospheric O_3 remained nearly constant after early Feb, whereas transport was expected to increase vortex O_3 substantially. This suggests additional chemical destruction of ~0.3-0.4 ppmv of vortex O_3. Figs. 2c and 2d show that the highest O_3 values were near the vortex edge throughout Feb and early Mar 1995. The transport calculations also result in maximum O_3 along the vortex edge (not shown), since strongest diabatic descent occurs there, but yield higher O_3 than observed in the vortex center. The observed 465 K O_3 morphology is thus due to a combination of chemical and dynamical effects. The transport calculation initialized on 28 Feb (Fig. 1c, open squares) implies that most of the O_3 change between then and 10 Mar can be explained by transport. Both inferred chemical O_3 loss and resupply by diabatic descent in late Feb/early Mar 1995 are smaller than during the (.01(1 spell in late Feb/early Mar 1994 [*Manney et al.,* 1995b].

Fig. 3 shows the O_3 change between 21 Dec 1994 and 3 Feb 1995 in PV/θ-space [e.g., *Schoeberl et al.,* 1989; *Manney et al.,* 1994]. The O_3 decrease was confined below ~520 K, and occurred throughout most of the vortex (Sold PV $\gtrsim$ 1.'2 x 1 0–⁴s–'). ClO was enhanced over a similar region. In the center of the vortex at tilt! lowest levels shown, the localized O_3 decrease was ~30%. Lidar observations [*Donovan et al.,* submitted to *Geophys. Res. Lett.*] show that the O_3 decrease extended to lower altitudes than are reliably observed by MLS.

column Ozone

Fig. 4 shows MLS column O_3 above 100 hPa on the same 4 days as the 465 K maps in Fig. 2. Transport increased maximum values of column O_3 between 21 Dec (Fig. 4a) and 3 Feb (Fig. 4b). As has been noted elsewhere [e.g., *Bojkov,* 1988], lowest temperatures and lowest column O_3 are approximately colocated. Minimum column O_3 in the vortex region decreased by ~10% between 21 Dec and 3 Feb. This decrease is consistent with chemical depletion, since the layer over which depletion was observed contributes ~1/3 of the column. However, dynamical effects also play a complex role in the evolution of column O_3 [e.g., *Bojkov,* 1988; *Petzoldt et al.,* 1994; 1994; *Randel and Wu,* 1995; and references therein]. Minimum column O_3 was slightly higher on 14 Feb and 8 Mar than on 3 Feb, but remained lower than on 21 Dec. During Feb and early Mar, a slight downward trend was seen in 60°-80°N average column O_3 (not shown), in contrast to previous years when MLS observed little or no trend.

Fig. 5 shows column O_3 on one day in each of the previous 3 winters observed by MLS, and in the 1978-79 winter observed by the Limb Infrared Monitor of the Stratosphere (LIMS). The selected days are near the time of minimum high latitude column O_3. The morphology of column O_3 in 1979, when stratospheric chlorine levels were sufficiently low and minimum temperatures sufficiently high [*Manney et al.,* 1994] that negligible chemical depletion was expected, clearly demonstrates that the pattern of low values in a confined region approximately coincident with lowest temperatures does not in itself indicate chemical depletion, as also noted by *Randel and Wu* [1995]. Minimum column O_3 in Jan 1992 (Fig. 5b) was as low as that in Feb 1995 (Fig. 4b); the low column O_3 in Jan 1992 is thought to have been primarily due to dynamical effects [e.g., *Petzoldt et al.,* 1994]. Minimum values observed in 1992-93 (Fig. 5c) and 1993-94 (Fig. 5d) were slightly higher than in 1994-95. Comparison with Fig. 1a shows that the column O_3 minima usually occur near the time of minimum temperature. An abrupt drop in column O_3 in early Mar 1994 (shown near its minimum in Fig. 5d) was contemporaneous with a large temperature decrease (Fig. 1a), and must be principally due to dynamical effects, since it is too large and occurs too quickly to be explained by chemical depletion. The 1994-95 MLS column O_3 was not substantially different, either in morphology or in amount, from that observed by MLS during other recent NH winters. That column O_3 was lower in early Feb (when temperatures were higher) than in late Dec may be indicative of chemical effects. *Bojkov et al.* [submitted to *Geophys. Res. Lett.*] showed observations of unusually low column O_3 over Siberia in Feb and Mar 1995, and suggested that that anomaly could not be explained solely by dynamical effects.

in early winter (Fig. 6a, 21 Jun 1994), S11 column O_3 is in all respects very similar to NH column O_3 (Fig. 4a). However, the contrast between SH and NH O_3 loss can be seen by comparing Fig. 4d with Fig. 6b. Minimum SH column O_3 above 100 hPa on 8 Sep 1994 was ~130 DU (typical for that season in the SH), in contrast to minimum values of ~200-215 DU seen during each of the NH winters. In the SH, lower stratospheric O_3 depletion is so severe that changes in column O_3 between early and late winter are dominated by chemical effects. In contrast, even during the 1994-95 NH winter, which was unusually cold for the NH and when substantial O_3 depletion was observed in the lower stratosphere, NH column O_3 changes are sufficiently small that the patterns are strongly influenced by dynamical processes, and chemical effects cannot readily be isolated.

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Figure 1. (a) Minimum 465 K vortex temperatures; vortex-averaged (b) ClO (ppbv) and (c) O_3 (ppmv) for 1 Dec through 20 Mar. Black dots in (b) and (c) show scanning MLS data in 1994 -95; dashed line in (b) shows ClO from non-scanning data (see text). Open symbols in (c) show transport calculations initialized on 21 Dec 1994 (triangles), 1 Feb 1995 (diamonds) and 28 Feb 1995 (squares).

Figure 2. 465 K MLS O_3 (ppmv) on 21 Dec 1994, 3 and 14 Feb, and 8 Mar 1995. The projection is orthographic, with 0° longitude at the bottom and 90°E to the right; dashed lines are at 30° and 60° N. 0.25 and 0.30 x 10^{-4} K m^2 kg^{-1} s^{-1} PV contours are overlaid.

Figure 3. O_3 change (ppmv) between 21 Dec 1994 and 3 Feb 1995, in PV/θ-space. PV is scaled in "vorticity units" to give a similar range of values at all levels shown. Black contours are 0.4, 0.6 and 0.8 ppbv of ClO averaged for"] , 3, and 8 Feb 1995, with highest values at highest 1'V. The PV contour used for vortex averages in Fig. 1 corresponds to a scaled PV of 1.2 X 10^{-4} s^{-1}. White contour is zero O_3 change.

Figure 4. As in Fig. 2, but for column O_3 above 100 hPa. 195 and 200 K temperature contours are overlaid.

Figure 5. As in Fig. 4, but for 9 Feb 1979 (from LIMS) and 13 Jan 1992, 2 Mar 1993 and 8 Mar 1994 (from MLS).

Figure 6. As in Fig. 5, but for 21 Jun and 8 Sèp 1994 in the SH. 0° longitude is at the top.

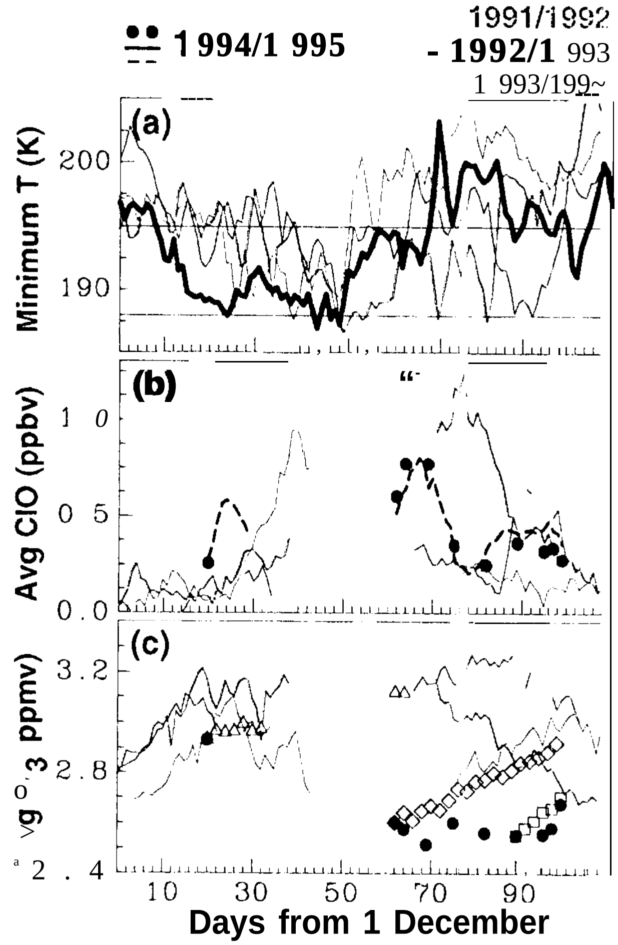

1994/1 995
1991/1992
- 1992/1 993
1 993/199~
(a)
Minimum T (K)
200
190
(b)
Avg ClO (ppbv)
1 0
0 5
0.0
(c)
vg O 3 ppmv)
3.2
2.8
2 . 4
10
30
50
70
90
Days from 1 December

Fig. 1

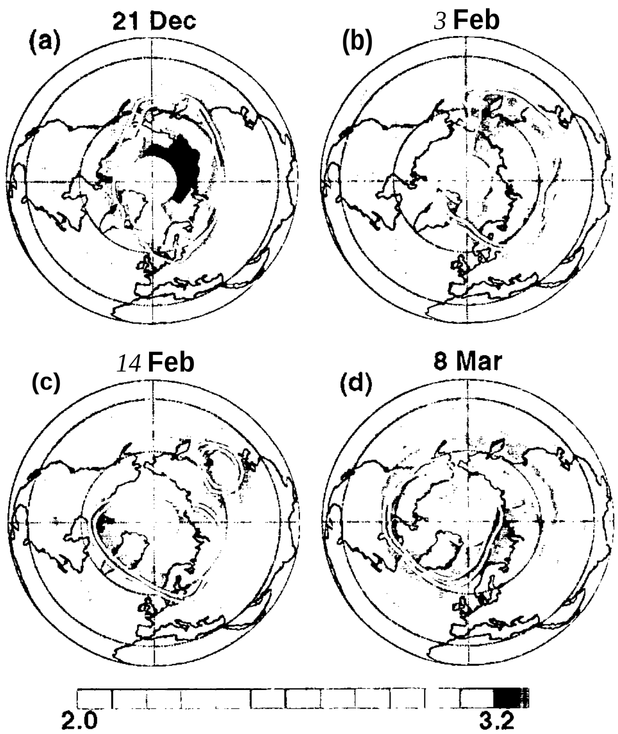
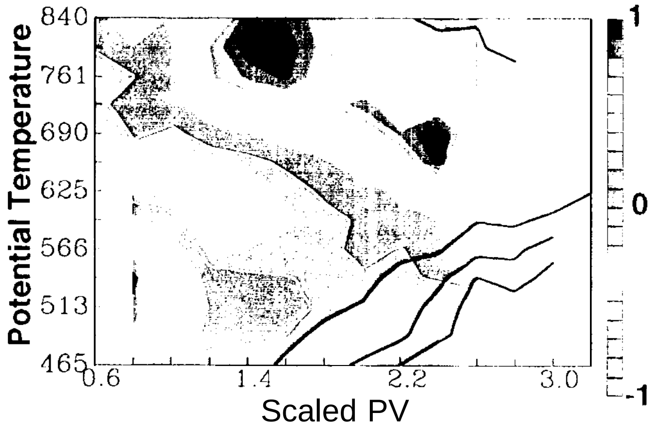


Fig. 2


Potential Temperature
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761
690
625
566
513
465
0.6
1.4
2.2
3.0
Scaled PV
1
0
-1

Fig. 3

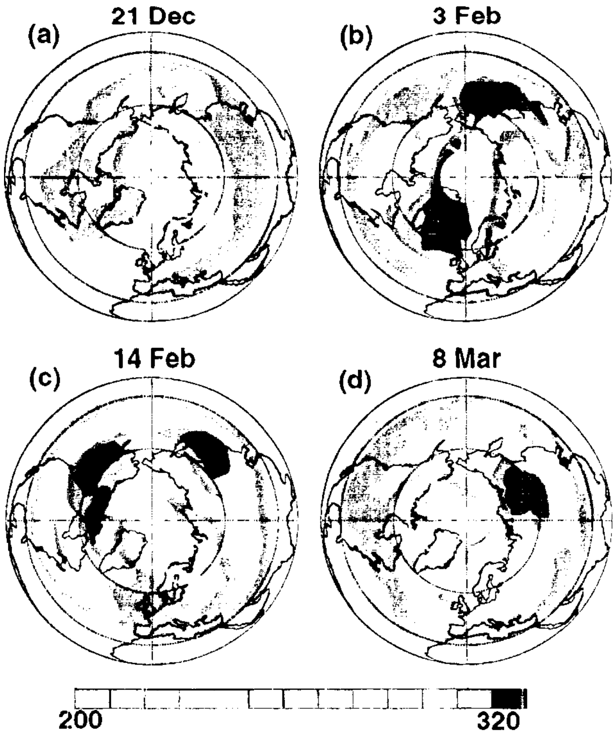

Fig. 4

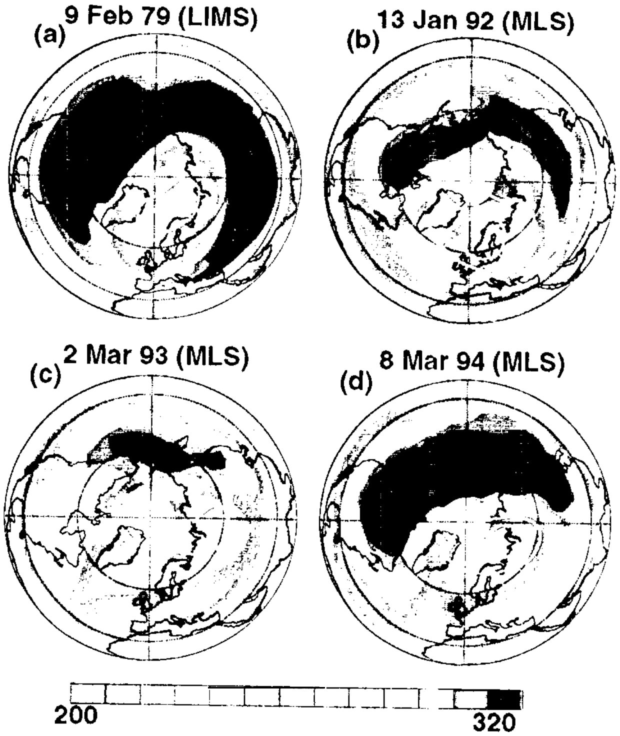

Fig. 5

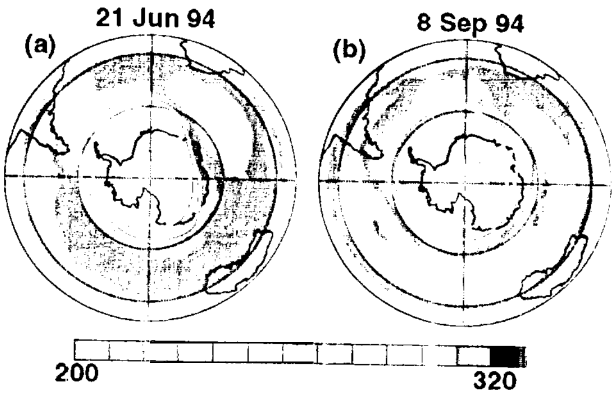

Fig. 6